Theoretical Study on Electroelastic Fracture Mechanics of Orthotropic Piezoelectric Materials(圧電効果を有する異方性材料の電気破壊力学に関する理論的研究)

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論文内容要旨

Chapter 1 Introduction

Piezoelectric materials and composites are an important branch of modern engineering materials, with wide applications in actuators and sensors in smart materials and structures [1, 2]. In most of these applications the piezoelectric crystal or ceramic is exposed to severe mechanical and electrical loading conditions which may result into structural failure or dielectric breakdown [3 – 5]. To prevent failure during service and to secure the structural integrity of piezoelectric devices, understanding of fracture process is of great importance [6 – 8].

In this paper, studies of cracked piezoelectric material systems are performed from a theoretical point of view.

Chapter 2 A simplified electroelasticity formulation of piezoelectric fracture

A viewpoint adopted in this chapter is to model cracked piezoelectric solids. The fundamental equations of the linear theory of classical piezoelectricity that will be used to study fracture behavior in piezoelectric solids are introduced, and the effects of crack face boundary conditions on the fracture mechanics are discussed [9, 10].

Canter 3 Anti-plane shear crack in a piezoelectric layer bonded to dissimilar half spaces

Following the theory of linear piezoelectricity, we consider the electroelastic problem for a piezoelectric layer with a crack bonded to two elastic half planes under antiplane shear loading. The crack parallel to the interfaces is in the mid-plane of the piezoelectric layer. Fourier transforms are used to reduce the problem to the solution of a pair of dual integral equations. The solution of the dual integral equations is then expressed in terms of a Fredholm integral equation of the second kind [9]. Numerical values on the stress intensity factor and the energy release rate for some piezoelectric laminates are obtained, and the results are graphed to display the electroelastic interactions.

Chapter 4 Layered piezoelectric media with an interface crack under antiplane shear loading

The antiplane shear problem for two dissimilar homogeneous materials bonded through a piezoelectric layer with a crack at the interface is considered. It is assumed that the layered piezoelectric medium is subjected to mechanical and electrical loading. By the use of Fourier transform techniques, the mixed boundary value problem is reduced to a singular integral equation [11]. The singular integral equation is solved numerically to determine the stress intensity factor for some layered piezoelectric media, and the results are presented in graphical form.

Chapter 5 The interface crack problem for bonded piezoelectric and orthotropic layers under antiplane shear loading

The primary objective of this Chapter is to study the influence of the electroelastic interactions on the stress intensity factor in bonded layers of piezoelectric and orthotropic materials containing a crack along the interface under antiplane shear. Attention is given to a two-layer hybrid laminate formed by adding a layer of piezoelectric ceramic to a unidirectional graphite/epoxy composite or an aluminum layer. Electric displacement or electric field is prescribed on the surfaces of the piezoelectric layer. The problem is formulated in terms of a singular integral equation which is solved by using a relatively simple and efficient technique [11]. A number of examples are given for various material combinations. The results show that the effect of the electroelastic interactions on the stress intensity factor can be highly significant.

Chapter 6 Scattering of antiplane shear waves by a finite crack in piezoelectric laminates

Following the dynamic theory of linear piezoelectricity, we consider the scattering of horizontally polarized shear waves by a finite crack in a composite laminate containing a piezoelectric layer [11]. The piezoelectric layer is bonded between two halfspaces of a different elastic solid. The crack is normal to the interfaces and is placed at an equal distance away from them. Both cases of a partially broken layer and a completely broken layer are studied. Fourier transforms are used to reduce the problem to the solution of a pair of dual integral equations. The solution of the dual integral equations is then expressed in terms of a singular integral equation. The propagation of symmetric first mode is studied numerically, and the dynamic stress intensity factor and the dynamic energy release rate are obtained for some piezoelectric laminates. We also investigate the scattering of Love waves by a surface-breaking crack in a layered piezoelectric solid [12].

Chapter 7 Electroelastic analysis of fatigue crack growth in a piezoelectric ceramic under longitudinal shear

We develop a fatigue crack growth equation of a finite crack in an orthotropic piezoelectric ceramic under longitudinal shear [13]. Dugdale's assumption regarding the plastic zone in thin metal sheets is applied to estimate the effects of yield around the crack tips. The problem is formulated by means of integral transforms and the solution is solved exactly. The accumulated plastic displacement criterion for crack propagation is used to develop equations to predict the fatigue crack growth, and a fourth-power stress intensity factor crack growth equation is derived.

Chapter 8 Fatigue crack propagation in a piezoelectric ceramic strip subjected to mode III loading

A forth-power stress intensity factor crack growth equation in an orthotropic piezoelectric ceramic strip is developed under mode III loading. The crack is situated symmetrically and oriented in a direction parallel to the edges of the strip. Fourier transforms are used to reduce the electroelastic problem to one involving the numerical solution of a Fredholm integral equation of the second kind [9]. Graphical results showing the effect of electroelastic interactions on the fatigue crack growth rate are presented.

Chapter 9 Fatigue crack growth of anti-plane shear crack normal to the edges of a piezoelectric ceramic strip

The theory of linear piezoelectricity is applied to develop a fatigue crack growth equation of a finite crack perpendicular to the edges of a piezoelectric ceramic strip under longitudinal shear. The technique consists of the reduction of the related dual integral equations of the problem to a Fredholm integral equation of the second kind [14]. Numerical values on the fatigue crack growth rate are obtained and the results are displayed numerically to exhibit the electroelastic interactions.

Chapter 10 Fatigue crack propagation in a piezoelectric ceramic strip subjected to mode I loading

A fatigue crack growth equation of a finite crack in an orthotropic piezoelectric ceramic strip under tensile loading is developed on the basis of the Dugdale model for plastic yielding near cracks in metals. The crack is situated in the mid-plane and is parallel to the edges of the strip. Use is made of integral transforms, which reduce the problem to the evaluation of a Fredholm integral equation of the second kind [15]. Based on the accumulated plastic displacement criterion for crack growth, a fatigue crack equation with fourth-power stress intensity factor dependence is developed. The numerical examples are given for some piezoelectric ceramics and the fatigue crack growth rate are plotted as a function of strip width to crack length ratio for various values of the electrical loads.

Chapter 11 Conclusions

The main results and conclusions of the present research work were summarized.

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審　査　結　果　の　要　旨

本論文は，知的材料・構造システムの設計・開発および信頼性・安全性評価のための圧電材料システムの電気破壊力学に関する理論的研究成果をまとめたもので，全編１１章からなる。

第１章の序論では，知的材料・構造システムの開発動向および本研究で対象とした圧電材料システムの電気破壊力学に関する研究の位置付けを述べると共に，本研究の目的と意義を明らかにしている。

第２章では，圧電材料システムの電気破壊力学的挙動を理論解析するため，き裂の電気弾性解析モデルを設定し，電気弾性基礎式を誘導している。

第３章～第６章は，縦せん断下における圧電積層材料を対象に，基本的な電気破壊力学的挙動を解明したもので，積分変換を用いた厳密な理論解析を行っている。先ず，第３章では，圧電層の上下両面に等方性弾性体が積層された圧電積層材料を取り上げ，圧電層に存在する界面に平行な内部き裂の電気弾性挙動を理論解析し，応力拡大係数およびエネルギー解放率に及ぼす電気弾性相互干渉の影響を解明している。また，第４章では，圧電層の上下両面にそれぞれ異なる等方性弾性体が積層された界面き裂を有する圧電積層材料の，第５章では，圧電層と異方性弾性層からなる界面き裂を有する圧電積層材料の電気破壊力学解析に成功し，界面き裂の電気弾性挙動を解明している。

続く第６章は，圧電層と等方性弾性体からなる圧電積層材料のき裂による縦せん断波散乱問題の理論解析に成功したもので，圧電層に存在する内部き裂は界面に垂直な場合を考えている。また，界面に垂直な縁き裂を有する圧電積層材料の Love 波散乱挙動についても，考察を加えている。さらに，これらの解析を破断層を有する圧電積層材料の電気破壊動力学解析に拡張し，破断層き裂の動的挙動を明らかにしている。

第７章～第１０章では，圧電セラミックスの疲労き裂成長挙動解明のための数理解析法を開発しており，先ず，第７章で，き裂を有する圧電セラミックスの，また，第８章および第９章で，縁に平行および垂直なき裂を有する圧電セラミックス帯板の縦せん断変形問題を取り上げ，疲労き裂成長挙動を解明している。続く，第１０章では，面内負荷を受ける縁に平行なき裂を有する圧電セラミックス帯板の電気弾性解析を平面ひずみを仮定して行い，疲労き裂成長に及ぼす電気弾性相互干渉の影響を明らかにしている。

最後に，第１１章の結論では，各章で述べた内容を概括すると共に，得られた知見を整理して本論文の統括としている。

以上要するに，本研究は，圧電材料システムの電気破壊力学的挙動の理論解析に成功し，知的材料・構造システムの電気弾性設計・開発・評価に資する結果を提供したもので，材料加工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。